

Elastic and inelastic cross section measurements with the ATLAS detector

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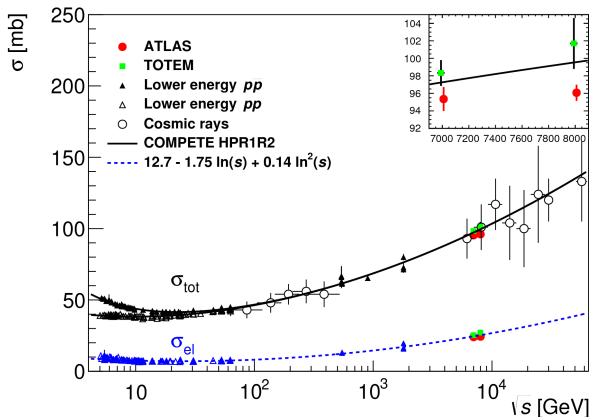
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Outline:

- Physics motivation.
- Inelastic cross section at $\sqrt{s} = 13$ TeV.
- Elastic, inelastic and total cross sections at $\sqrt{s} = 8$ TeV.
- Future elastic measurements.

- The elastic (σ_{el}), inelastic (σ_{inel}) and total (σ_{tot}) pp cross sections are fundamental quantities which cannot be calculated with perturbative QCD.
- Regge theory provides general description but data is needed to constrain models.
- σ_{tot} gives the upper bound on any pp process and is observed to rise with \sqrt{s} .
- A substantial fraction of σ_{inel} is diffractive processes and a measurement of σ_{inel} gives better background determination for high p_T processes.



Inelastic cross section measurement at $\sqrt{s} = 13$ TeV

Phys. Rev. Lett. 117 (2016) 182002

Inelastic cross section at 13 TeV - Strategy

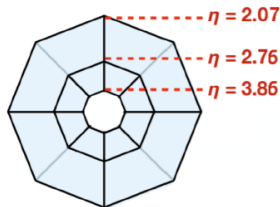
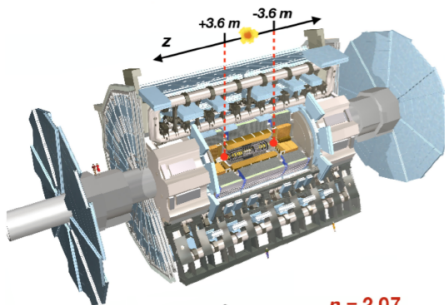
- Measure the σ_{inel} in a fiducial region and extrapolate to full phase-space using simulations.
 - The better detector coverage, the smaller extrapolation uncertainty.

- ATLAS uses the MBTS plastic scintillator discs at $z = \pm 3.6$ m covering $2.07 < |\eta| < 3.86$

- Corresponds to

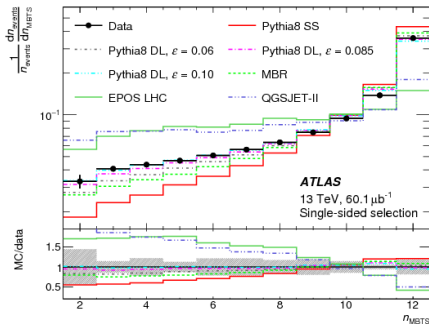
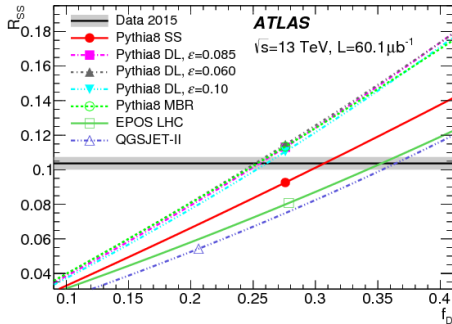
$$\xi \equiv M_x^2/s > 10^{-6}.$$

- 8 inner and 4 outer counters in each disc.
 - $\sim 99\%$ efficiency for charged particles.
- The fiducial σ_{inel} is the number of observed events with ≥ 2 hits corrected for background, pile-up, efficiencies and luminosity.
- Use $60 \mu\text{b}^{-1}$ of pp collisions at $\sqrt{s} = 13$ TeV with $\mu \sim 0.002$



Inelastic cross section at 13 TeV - Tuning models

- The inelastic cross section is the sum of the non-diffractive and the diffractive cross section.
- The ratio $f_D = (\sigma_{SD} + \sigma_{DD})/\sigma_{inel}$ is poorly known and differs between models.
- The fraction of single-sided events, R_{SS} , is related to f_D and used to tune f_D in the models.
- Using the f_D -tuned models, the hit multiplicity in the MBTS for the models are compared to data:
 - The DL (Donnachie-Landshoff) pomeron flux model is best.
 - ϵ is a free parameter in the pomeron Regge trajectory.
 - The EPOS LHC and QGSJET-II models (developed mostly for cosmic-ray showering) are worst.

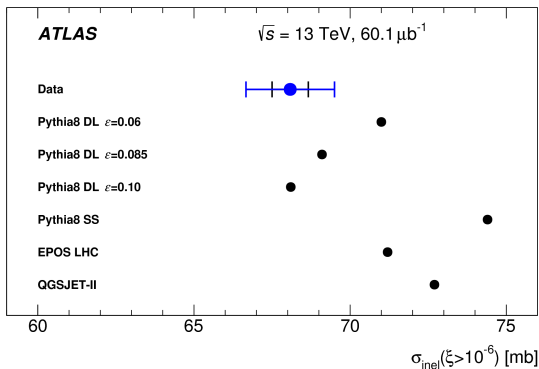


Inelastic cross section at 13 TeV - Results

- The fiducial inelastic cross section in $\xi > 10^{-6}$ is measured to be

$$\sigma_{\text{inel}}^{\text{fid}} = 68.1 \pm 0.6_{(\text{exp.})} \pm 1.3_{(\text{lum.})} \text{ mb}$$

- This is in good agreement with the Pythia8 DL model.



(inner error bars are without luminosity uncertainty)

Inelastic cross section at 13 TeV - Results

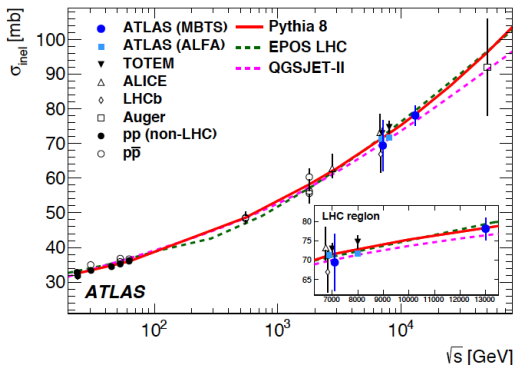
- The fiducial cross section is extrapolated to the full phase space using the Pythia8 DL and MBR models:

$$\sigma_{\text{inel}} = 78.1 \pm 0.6_{(\text{exp.})} \pm 1.3_{(\text{lum.})} \pm 2.6_{(\text{extr.})} \text{ mb}$$

- The inelastic cross section is still increasing with \sqrt{s} .
- This is in agreement with model predictions.
- The CMS result is:

$$\sigma_{\text{inel}} = 71.3 \pm 3.5 \text{ mb}$$

which is a 1.5σ difference.



Elastic, inelastic and total cross sections measurement at $\sqrt{s} = 8$ TeV

Phys. Lett. B 761 (2016) 158-178

- From the optical theorem we get:

$$\sigma_{\text{tot}}^2 = \frac{16\pi(\hbar c)^2}{1 + \rho^2} \frac{1}{L} \left. \frac{dN_{\text{el}}}{dt} \right|_{t=0} \quad \text{with} \quad \rho \equiv \frac{\text{Re}[F_{\text{el}}(t=0)]}{\text{Im}[F_{\text{el}}(t=0)]}$$

- The four-momentum transfer t is calculated as

$$-t = (\mathbf{p} \times \boldsymbol{\theta}^*)^2.$$

where the scattering angle $\boldsymbol{\theta}^*$ is calculated from the proton trajectories and \mathbf{p} is the beam momentum.

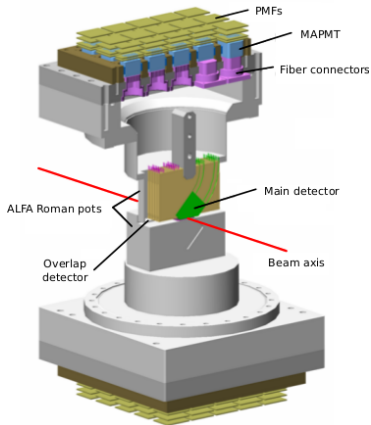
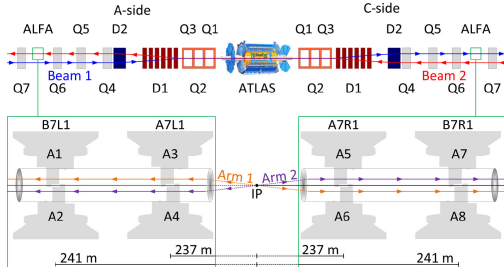
- Minimum accessible t -value is given by

$$-t_{\text{min}} \propto \frac{d^2}{\beta^*}$$

- Use $500 \mu\text{b}^{-1}$ with a $\beta^* = 90$ m collision optics and low pile-up ($\mu \approx 0.1$).
 - Standard LHC running uses $\beta^* \sim 0.5$ m.

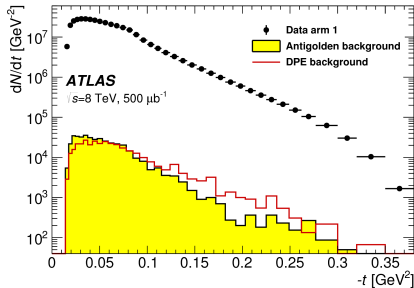
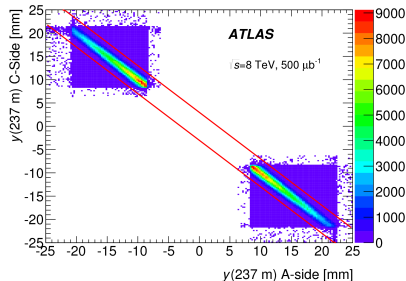
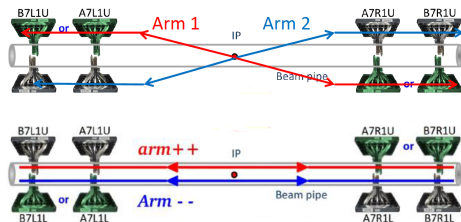
Elastic analysis at 8 TeV - The ALFA detector

- Built to measure elastically scattered protons at μrad angles.
- Located 240 m from the ATLAS interaction point inside Roman Pots.
- The main detector is built of scintillating fibers.
 - The fiber width of $500\ \mu\text{m}$ and layer staggering gives $\approx 30\ \mu\text{m}$ tracking resolution.
- The scattering angle is reconstructed from the tracks using knowledge about the LHC magnet strengths.



Elastic analysis at 8 TeV - Data analysis

- Events are selected when all four detectors in an arm have a track.
- Momentum conservation provides strong selection cuts.
- Total number of elastic candidates is 3.8 M.
- Background level is 0.12 % estimated from the antigolden topology.
 - Primarily Double Pomeron Exchange (DPE).
- Observed t -spectrum is corrected for acceptance, detector resolution, luminosity, and efficiencies.



- The differential elastic cross section is a superposition of the strong interaction amplitude F_N and the Coulomb amplitude F_C added in quadrature giving

$$\frac{d\sigma_{\text{el}}}{dt} \propto \frac{G^4(t)}{|t|^2} + \sigma_{\text{tot}}^2 (1 + \rho^2) \cdot \exp(-B|t|) - \frac{\sigma_{\text{tot}} G^2(t)}{|t|} [\sin(\phi(t)) + \rho \cos(\phi(t))] \cdot \exp\left(\frac{-B|t|}{2}\right)$$

- The fit range is $0.014 \leq |t| \leq 0.1 \text{ GeV}^2$.
- The unfolded differential cross section is fitted with σ_{tot} and B as free parameters.

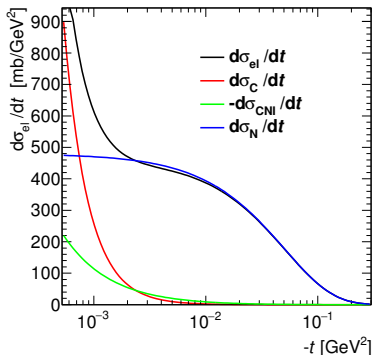
- No sensitivity to:**

- The ρ -parameter fixed to 0.1362 from COMPETE predictions.
- The interference phase taken as:

$$\phi(t) = -\ln\left(\frac{B|t|}{2}\right) - \gamma_E$$

- The proton form factor taken as:

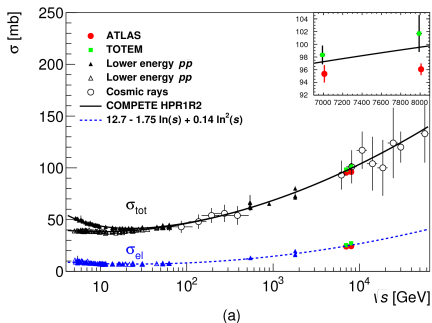
$$G(t) = \left(\frac{\Lambda}{\Lambda + |t|}\right)^2, \quad \Lambda = 0.71 \text{ GeV}^2$$



- The result for the total cross section is:

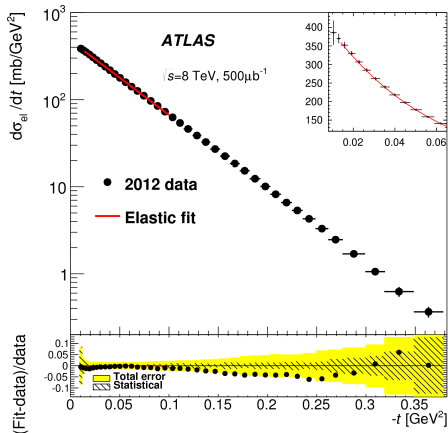
$$\sigma_{\text{tot}} = 96.07 \pm 0.18_{(\text{stat})} \pm 0.85_{(\text{exp.})} \pm 0.31_{(\text{extr.})} \text{ mb.}$$

σ_{tot} is still rising with energy.



(fit not updated with latest ATLAS result)

Unfolded t -spectrum:



- The elastic cross section σ_{el} is the integral of the nuclear part:

$$\sigma_{el} = 24.33 \pm 0.04_{(stat.)} \pm 0.39_{(syst.)} \text{ mb .}$$

- The inelastic cross section is the difference between the total and the elastic:

$$\sigma_{inel} = 71.73 \pm 0.15_{(stat.)} \pm 0.69_{(syst.)} \text{ mb .}$$

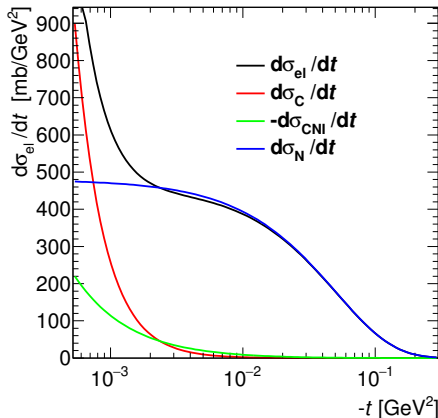
- This is about 4 times more precise than the direct measurement at 13 TeV (page 7):

$$\sigma_{inel}^{13 \text{ TeV}} = 78.1 \pm 0.6_{(exp.)} \pm 1.3_{(lum.)} \pm 2.6_{(extr.)} \text{ mb}$$

- The extrapolation uncertainty on σ_{inel} from elastic scattering comes from a simple fit range variation.

- Data in the Coulomb-Nuclear-Interference region at $-t \approx 10^{-3} \text{ GeV}^2$ allows a measurement of the ρ -parameter.
 - Provides insight to the understanding of elastic scattering.
 - Dispersion relations derived from analyticity relates energy evolution of the σ_{tot} and ρ .
 - The simultaneous measurement of σ_{tot} and ρ therefore tests a very basic assumption.
 - High energy predictions of σ_{tot} will be possible.

- Data has been collected at $\sqrt{s} = 8 \text{ TeV}$ with $\beta^* = 1 \text{ km}$ optics.
 - **The analysis is in review.**
- Data has been collected at $\sqrt{s} = 13 \text{ TeV}$ with $\beta^* = 2.5 \text{ km}$ optics.
 - The analysis is ongoing.



Inelastic cross section at $\sqrt{s} = 13$ TeV:

- The diffractive fraction in several models are tuned to match an observable in data.
- The fiducial cross section agrees well with Pythia8 DL model.
- The full inelastic cross section is in agreement with models and is still observed to rise with \sqrt{s} .

Total cross section at $\sqrt{s} = 8$ TeV:

- The differential elastic cross section is measured with tracking detectors in Roman pots.
- The total cross section is inferred using the optical theorem and is still observed to rise with \sqrt{s} .
- Future measurements of the ρ -parameter will provide further insight to the non-perturbative regime of QCD.

Backup slides

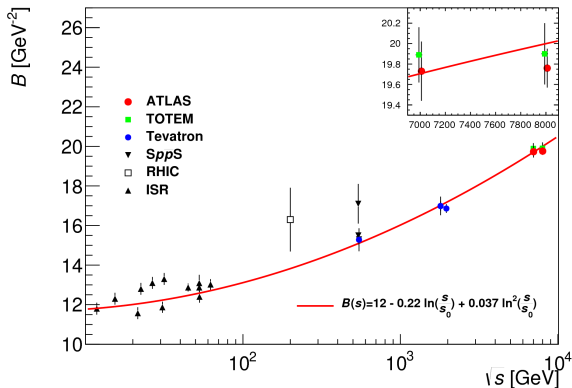
Backup - Investigations of nuclear slope parametrization

- Different parametrizations for the nuclear slope have been investigated.
- The upper limit of the fit range was increased to $|t| = 0.3 \text{ GeV}^2$ in order to increase the sensitivity of additional parameters.
- The quality of the fit is increased due to the higher number of free parameters.

	$\sigma_{\text{tot}}[\text{mb}]$	Model
Nominal	96.07 ± 0.86	$f_{\text{N}}(t) = (\rho + i) \frac{\sigma_{\text{tot}}}{\hbar c} e^{-Bt/2}$
Ct^2	96.16 ± 0.80	$f_{\text{N}}(t) = (\rho + i) \frac{\sigma_{\text{tot}}}{\hbar c} e^{-Bt/2 - Ct^2/2}$
$c\sqrt{-t}$	96.40 ± 0.80	$f_{\text{N}}(t) = (\rho + i) \frac{\sigma_{\text{tot}}}{\hbar c} e^{-Bt/2 - c/2(\sqrt{4\mu^2 - t} - 2\mu)}$, $\mu = m_{\pi}$
SVM	96.16 ± 0.80	$f_{\text{N}}(t) = \rho \frac{\sigma_{\text{tot}}}{\hbar c} e^{-B_R t/2} + i \frac{\sigma_{\text{tot}}}{\hbar c} e^{-B_I t/2}$
BP	96.81 ± 0.95	$f_{\text{el}}(t) = i \left[G^2(t) \sqrt{A} e^{-Bt/2} + e^{i\phi} \sqrt{C} e^{-Dt/2} \right]$
BSW	96.67 ± 0.99	$\text{Re} f_{\text{el}}(t) = c_1(t_1 + t) e^{-b_1 t/2}$, $\text{Im} f_{\text{el}}(t) = c_2(t_2 + t) e^{-b_1 t/2}$

Backup - Results for the nuclear B-slope

- ATLAS measurement: $B = 19.73 \pm 0.24 \text{ GeV}^{-2}$
- TOTEM measurement: $B = 19.9 \pm 0.3 \text{ GeV}^{-2}$
- Pre-LHC expectations was a linear evolution of the B -slope with $\ln(s)$
- LHC measurements of the B -slope favours a second $\ln^2(s)$ term.

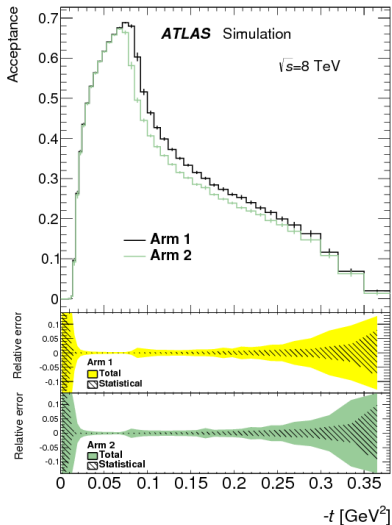
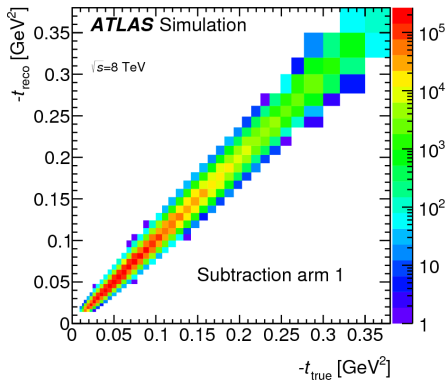


(b)

(fit not updated with latest ATLAS result)

Backup - Acceptance and resolution

- **Detector acceptance** is highly dependent on detector distance to the beam and beam divergence.
 - Found from simulation tuned to data.
- **t -resolution** is influenced by detector resolution and beam divergence.
 - Relative t -resolution is better than 10 % and corrected for by unfolding.



Backup - Beam optics corrections

- The beam optics has direct influence on the t -reconstruction.
- Different t -reconstructions gives different results
⇒ the initial **design** optics needs modifications.
- Elastic data is used to constrain an optics fit including magnet strengths whereby an **effective** optics is obtained.

